AAS 02-225

American Astronautical Society

Using Available DSN Tracking Coverage as a Design Parameter in Mission Proposals

A look at a simulated mission, and the effect upon the DSN load based upon different launch opportunities

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12th AAS/AIAA Space Flight Mechanics Meeting
27 - 30 Jan 2002
San Antonio, Texas

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The work described was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

Abstract

The way a Proposed Deep Space Mission is designed should be linked to additional design parameters/ constraints such as the availability of the Deep Space Network to support communications. This paper explores this exact methodology by examining the launch opportunities of a simulated mission to Jupiter during a decade long timeframe. By using the tools MADB & TIGRAS, alternate launch dates during this window were examined from a perspective of the ability of the DSN to provide the tracking coverage needed during the mission critical events. The results of this multi-dimensional analysis are presented at the end of this paper, with a ranking of which launch windows are preferable relative to the other possible launch windows.

Why consider DSN Support when designing a Mission Proposal?

The objective of a mission proposal is to obtain approval (and funds) for the next phase of development, and ultimately to become a fully funded/flying mission. Such missions require the support of the Deep Space Network (DSN) to return tracking and science data. When downselecting between the many Proposals submitted, how a Proposal fits within the available support of the DSN is a grading criteria. When viewed in this light, it can be seen that Proposals which only exacerbate the (traditional) over-subscription of the DSN tracking assets are less likely to be selected when compared to a Proposal of comparable merit that fits within the ability of the DSN to provide the necessary/desired tracking support.

Using the Jovian Moon Explorer (JME) Simulated Mission to illustrate the point, it is possible to inadvertently plan the mission critical Jovian Moon Orbit Insertion Maneuver, and the Prime Mission data collection at a time when the line of sight to Jupiter *includes* Mars. In such a case, obtaining the critical tracking coverage for the JME Mission would contend directly with the tracking needs of all the missions already in Mars orbit. This would not be nearly as favorable as a JME arrival time which is deliberately selected such so there is no overlap/contention with the tracking time desired by the Mars Programs.

This is how consideration of the availability of DSN assets can be best used to increase a Proposal's probability of being funded to the next level of Project/Program development.

What is the Jovian Moon Explorer Mission?

The Jovian Moon Explorer (JME) Mission is a simulated mission that was constructed solely for the purpose of this paper. This simulated mission then is used to illustrate the ability of the DSN to provide the necessary tracking coverage, so that different options can be assessed. In order to do this, several mission requirements and objectives, representative of an actual Proposal were created, including the following:

Jovian Moon Explorer Simulated Mission Objectives:

- 1 Month Prime Mission at a Jovian Moon; mapping and taking observations.
- 1 Month Extended Mission, once prime mission objectives have been achieved.
- 1 Month Post Extended Mission, once extended mission objectives have been achieved. (spacecraft survival is presumed to be limited by lifetime radiation dosage).

The JME spacecraft propulsion is specified as:

- Impulsive (conventional) Thrust.

The JME mission trajectory parameters are:

- 2005 Jan 01: Earliest Launch Date.
- 2018 Dec 31: Latest Launch Date.
- The Trajectory used to reach Jupiter is not further constrained.
- 1 1/2 years to reduce the Orbit at Jupiter from Initial Capture to actual operational orbit/ data collection altitude above the surface of the Jovian Moon.

Trajectory Options

The most straightforward trajectory is a direct Earth-Jupiter (EJ) trajectory, which is illustrated below in Figure 1. This EJ class of launch opportunity repeats approximately every 13 months, and every window between Jan 01, 2005 and Dec 31, 2018 was investigated[1]. Summary data is presented below in Table 1.

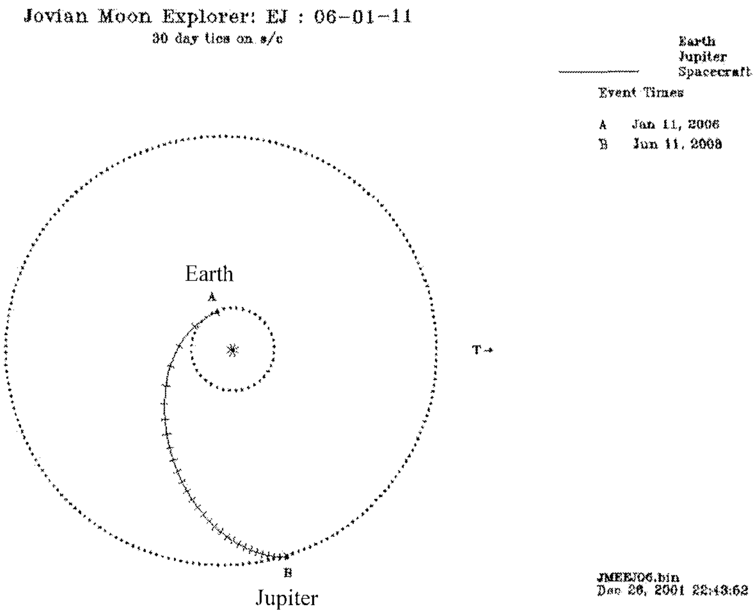


Figure 1: Example of The Direct Earth-Jupiter Trajectory

There are other classes of trajectories which can be investigated, but are beyond the scope of this effort.

A second class of trajectories exist, which include launching direct from Earth into an intermediate "two year" orbit around the sun, performing an Earth Swingby, then followed by the Earth – Jupiter trajectory as illustrated in Figure 1.

Additionally, there are possibilities for using other planetary bodies for swingby maneuvers (Project *Galileo* used a Venus–Earth–Earth–Jupiter trajectory, while Project *Cassini* used a Venus–Venus–Earth–Jupiter trajectory). Limiting the analysis to the direct Earth–Jupiter is not intended to provide a definitive answer to the complex issue of the overall mission design for the JME Mission. Rather, this is done to reduce the trade space considered so that the impact of the availability of the DSN to provide to provide tracking passes can be clearly illustrated.

Additionally, since the nominal alignment of the Galilean Satellites repeats multiple times (orbital periods of 1.7 days (Io), 3.6 days (Europa), 7.2 days (Ganymede), and 16.7 days (Callisto)) during the eighteen months allotted to reduce the orbit/achieve final orbit around the Jovian Moon, the actual mechanics of the orbit reduction campaign is posited as existing, but left unsolved for the purposes of this paper. This simplification permits the use of the planet Jupiter to model the JME trajectory between post Jupiter Orbit Insertion and the actual Jovian Moon Arrival. While important for actually tracking the spacecraft, the distinction between the actual Jovian Orbit Reduction campaign and the viewperiods used is not significant for the purposes of determining the antenna loading. The pass duration remains effectively unchanged (between nine and thirteen hours), and to alter the start time of the pass by five minutes, the JME spacecraft would have to be more than ~11 million kilometers (~7 million miles) from Jupiter[2].

Table 1: Direct Earth-Jupiter Launch Opportunities

Launch Date	Mission Duration (years)	Trajectory Launch C3 (km^2/s^2)	Deep Space Maneuver
12/21/2004	4.97	76.40	No
01/11/2006	4.16	75.90	No
02/13/2007	3.86	79.11	No
04/01/2008	4.93	76.93	YES
05/22/2009	5.43	82.77	No
06/06/2010	3.92	83.39	No
07/11/2011	4.15	80.06	No
08/14/2012	3.90	85.60	No
10/25/2013	6.52	87.54	No
10/20/2014	3.87	91.50	No
11/20/2015	3.96	88.42	No
12/23/2016	4.87	75.98	No
01/16/2018	4.09	76.28	No

Tracking Requirements During the Mission

To answer the question of whether the requested tracking coverage for a mission can be provided, in addition to the trajectory information (which is necessary to generate the viewperiods for the mission), the actual tracking requirements for the mission must also be known. The spacecraft requires monitoring at regular intervals, with specific/major events requiring additional tracking and communication. The list of events, and the associated tracking requirements is listed below:

- Launch
  continuous tracking to +30 days
- Interplanetary Cruise
  two 8-hour passes per week
- Deterministic Deep Space (DSM) Maneuvers
  continuous tracking from -2 day to +1 days
- Jupiter Arrival / Jupiter Orbit Insertion Maneuver
  one 8-hour pass per day from -60days to -3 days
  continuous tracking from -3 days to +3 days
- Jupiter Orbit Reduction (including Galilean Satellite Swingbys)
  three 8-hour passes per week
- Jovian Moon Arrival / Final (Operational) Orbit Insertion Maneuver
  one 8-hour pass per day from -30days to -3 days
  continuous tracking from -3 days to +3 days
- Prime Mission Operations (at the Jovian Moon)
  continuous tracking support (from Day 04 through Day 34)
- Extended Mission Operations (at the Jovian Moon)
  continuous tracking support (from Day 35 through Day 65), which can be reduced to two 8-hour passes per day if necessary to alleviate antenna resource over-subscription.
- Post-Extended Mission Operations (at the Jovian Moon)
  two 8-hour passes per day (from Day 66 through Day 96), which can be reduced to one pass per day if necessary to alleviate antenna resource over-subscription.

Ranking the specific Trajectory Options

There are many dimensions/factors involved in conducting the mission design process for a mission. One aspect might be maximizing spacecraft mass; another might be reducing total mission duration. These rankings are presented in Table 2.

Table 2: Various JME Rankings

Launch Date	SC Mass Ranking	Duration Ranking
12/21/2004	- -	- -
01/11/2006	1)	8)
02/13/2007	4)	1)
04/01/2008	6)	10)
05/22/2009	7)	11)
06/06/2010	8)	4)
07/11/2011	5)	7)
08/14/2012	9)	3)
10/25/2013	10)	12)
10/20/2014	12)	2)
11/20/2015	11)	5)
12/23/2016	2)	9)
01/16/2018	3)	6)

Other aspects to consider are whether the timing and geometry of mission critical events, such as the Jovian Moon Orbit Insertion, are acceptable. When viewed from this last perspective, the 05/22/09 Trajectory is not viable, because the Jovian Moon Orbit Insertion Maneuver occurs on 07/26/14, a time when the Sun–Earth–Spacecraft angle only 0.92 degrees. Conjunction formally occurs two days earlier (0.41 degrees), and the spacecraft does not reach ten degrees of separation until 08/07/14. This is important because reliable two-way communication/tracking of the spacecraft is not dependable until that date, which means that the mission critical Jovian Moon Orbit Insertion Maneuver would have to be either rescheduled, or conducted "in the blind", and the results of that maneuver would not be known for a week and a half.

Another dimension to the mission design process is the ability of the Deep Space Network to provide the tracking coverage for the spacecraft, which is the focus of this paper.

Figure 2 shows the percentage overlap between the viewperiods[3] for the Jovian Moon Explorer and the viewperiods for the Sun and Mars. This particular slice of the viewperiod overlaps is presented because of the number of missions that are projected to be at Mars[4], and the corresponding projected over-subscription of the available resources (antennas) during that particular time of the day.

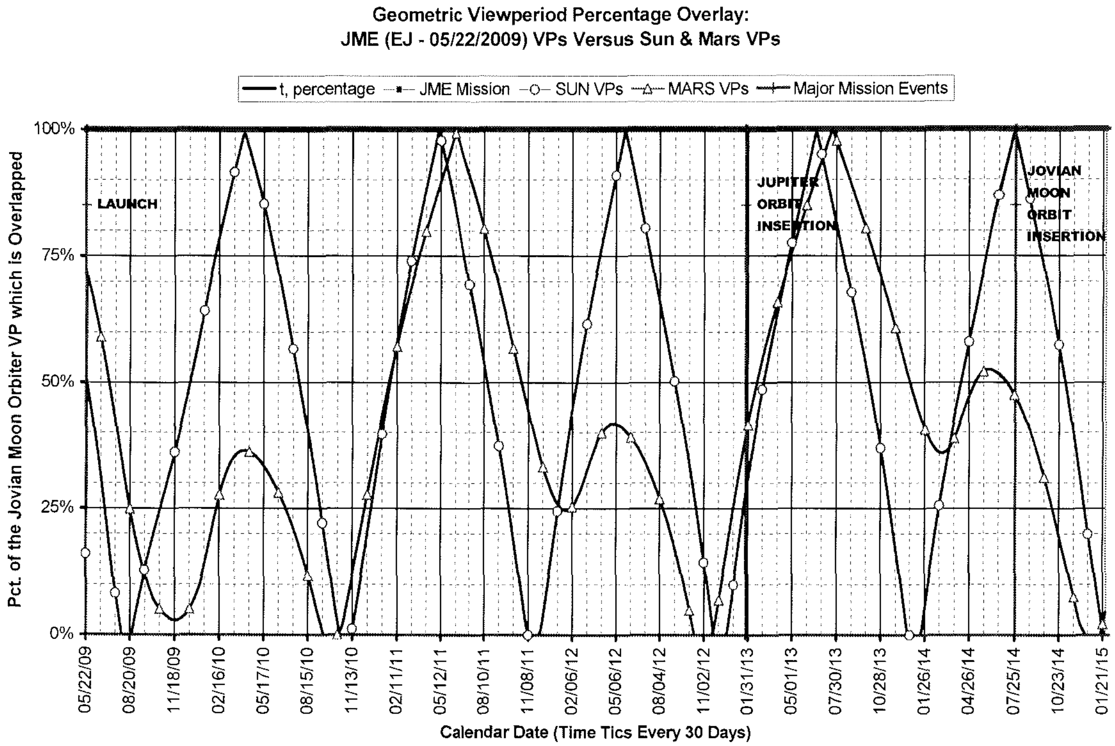


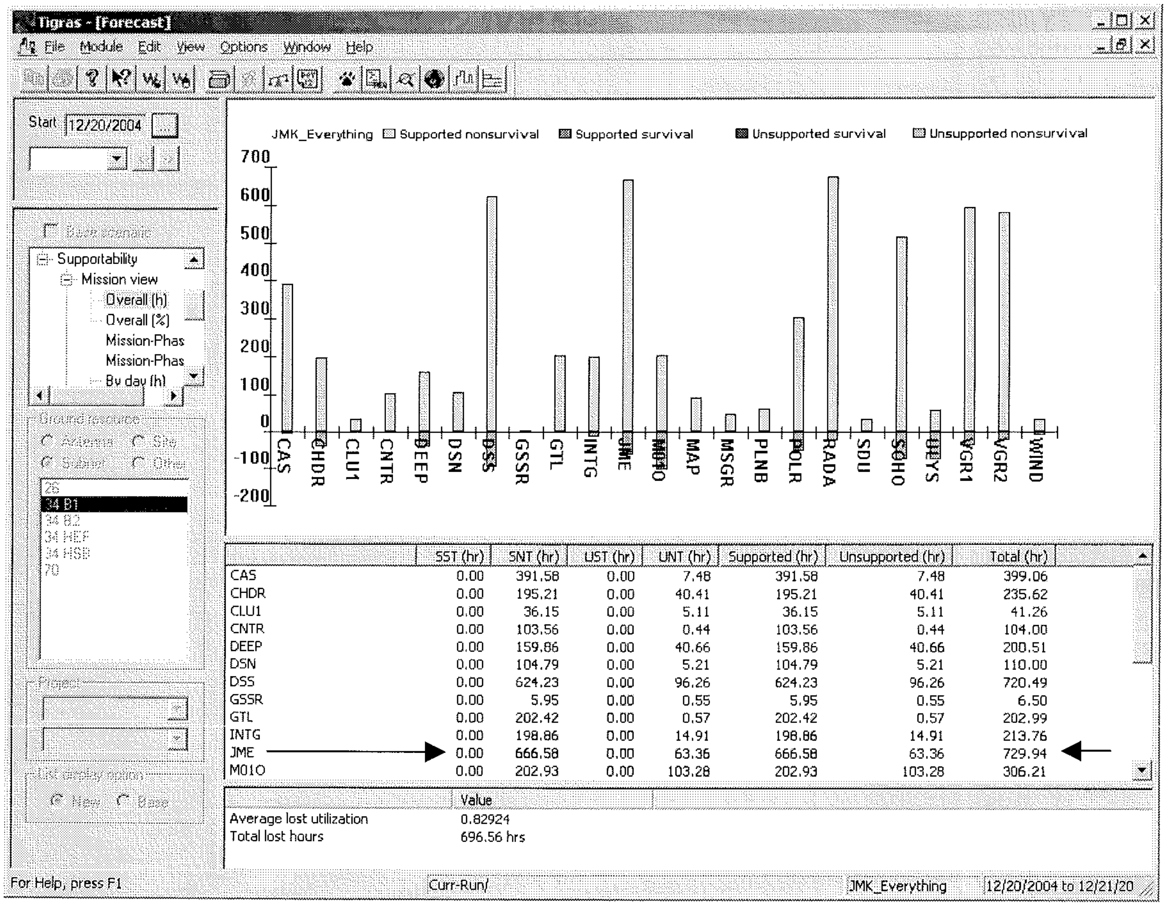
Figure 2: Overlap between Tracking Coverage for JME and the Sun and Mars Viewperiods

In Figure 2, the high overlap with the viewperiods for the Sun at Jovian Moon Orbit Insertion can be seen, in addition to the fact that the geometric overlap with the viewperiods for Mars is approximately 50%. To better understand the level of contention which exists between the JME and the various Mars Spacecraft, the JME simulated mission was broken down according to phase, and the results are presented in Table 3.

Table 3: JME Tracking Coverage Overlap between JME and Mars Viewperiods

Launch Date	Launch-L+30d	EJ Cruise	JOI - 30d JOI + 5d	Orbit Reduction	Moon Approach	Prime Mission	Extended Mission
12/21/2004	54.3%	26.3%	1.7%	50.8%	25.3%	10.6%	0.5%
01/11/2006	10.8%	41.5%	2.9%	52.8%	0.0%	0.0%	8.9%
02/13/2007	45.4%	22.2%	91.4%	22.6%	4.3%	15.8%	36.4%
04/01/2008	0.2%	43.6%	92.9%	33.1%	2.9%	18.5%	42.3%
05/22/2009	64.8%	34.6%	32.7%	64.0%	49.8%	44.1%	30.6%
06/06/2010	0.2%	48.6%	25.4%	53.6%	42.8%	36.8%	41.5%
07/11/2011	61.6%	40.8%	61.5%	33.2%	58.6%	69.3%	82.8%
08/14/2012	2.6%	57.2%	28.9%	54.8%	49.8%	46.6%	54.1%
10/25/2013	76.1%	54.0%	41.3%	34.7%	77.9%	87.2%	93.4%
10/20/2014	4.0%	60.2%	24.3%	53.7%	47.9%	40.6%	42.5%
11/20/2015	67.7%	44.4%	92.8%	35.6%	29.9%	41.7%	54.2%
12/23/2016	1.6%	50.1%	80.3%	52.7%	0.2%	1.4%	16.1%
01/16/2018	71.1%	41.9%	80.5%	35.5%	27.2%	36.8%	52.1%

Broken out by phase, the 05/22/2009 JME Launch opportunity can be seen to have overlaps with the Mars viewperiods of 49.8% during the month prior to Jovian Moon Orbit Insertion Maneuver, 44.1% during the Prime Mission, and 30.6% during the Extended Mission Phase. However, a simple geometric overlap in viewperiods does not imply an inability to provide the requested tracking coverage. The specific TIGRAS loading analysis for the Launch Phase of the Dec 21st 2004 JME Launch Opportunity (54.3% overlap) illustrates this point:



	SST (hr)	SNT (hr)	UST (hr)	UNT (hr)	Supported (hr)	Unsupported (hr)	Total (hr)
CAS	0.00	391.58	0.00	7.48	391.58	7.48	399.06
CHDR	0.00	195.21	0.00	40.41	195.21	40.41	235.62
CLU1	0.00	36.15	0.00	5.11	36.15	5.11	41.26
CNTR	0.00	103.56	0.00	0.44	103.56	0.44	104.00
DEEP	0.00	159.86	0.00	40.66	159.86	40.66	200.51
DSN	0.00	104.79	0.00	5.21	104.79	5.21	110.00
DSS	0.00	624.23	0.00	96.26	624.23	96.26	720.49
GSSR	0.00	5.95	0.00	0.55	5.95	0.55	6.50
GTL	0.00	202.42	0.00	0.57	202.42	0.57	202.99
INTG	0.00	198.86	0.00	14.91	198.86	14.91	213.76
JME	0.00	666.58	0.00	63.36	666.58	63.36	729.94
M01O	0.00	202.93	0.00	103.28	202.93	103.28	306.21

	Value
Average lost utilization	0.82924
Total lost hours	696.56 hrs

Figure 3: TIGRAS Screen Capture of DSN Antenna Loading for Launch Phase of 2004 JME Mission

As can be seen in Figure 3, as both bar charts and actual hours, *despite* the 54.3% geometric overlap in viewperiods, nearly all (666.58 supported hours of 729.94 total hours) of the Launch Support coverage for the JME mission can be provided (the arrows have been edited into the screen capture for the purposes of clarity). This is due to a combination of factors, including the priority of providing Launch Phase tracking coverage for a mission, the fact that there are multiple antennas, which can provide tracking support (70M, 34HSB, 34HEF, 34B2, and 34B1), and the level of tracking support requested by the other missions.

Conversely, there are times when tracking coverage cannot be supported despite the critical need for that tracking support. This is illustrated in Figure 4, presented on the next page. This specific case study was the result of one of the parametric studies, which was performed in support of this paper. The date of Jovian Moon Arrival was altered to determine the ability of the Deep Space Network to provide the required tracking coverage on that date. As can be seen in Figure 4, although the Jovian Moon Explorer (JME) is in Prime Mission during this timeframe, it is not possible to provide the mission with continuous coverage as set forth in the Tracking Requirements for the JME Simulated Mission. This is the result of a combination of several unfavorable factors, which include high demand for tracking support by the individual Projects, combined with geometric viewperiod overlap. The view in Figure 4 is particularly useful when conducting in depth studies, because it displays the missions to which the tracking coverage is competitively lost, and the amount of tracking time that is lost to each project.

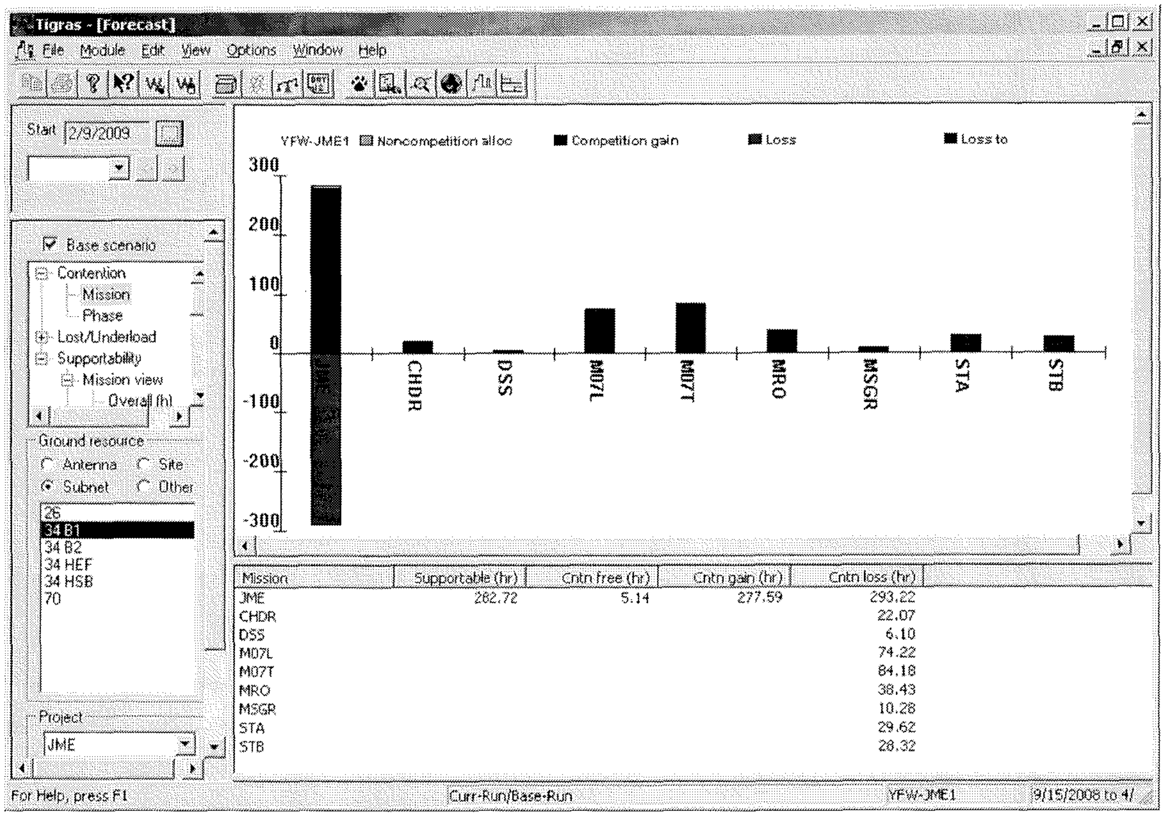


Figure 4: TIGRAS screen capture showing unsupportable tracking time, and to which missions (CHDR, DSS, M07L, M07T, MRO, MSGR, STA, STB) that time is competitively lost.

The result of this case study was not favorable: over half of the required tracking time during the Prime Mission Phase for the JME Mission could not be provided.

Optimizing the JME Trajectories to maximize availability of Tracking Support

Given that this paper is considering only the Direct Earth-Jupiter class of trajectories for the JME Mission, there is limited flexibility in altering certain aspects of the trajectory. Earth Launch and Jupiter Arrival cannot be altered, without significant performance penalties (which translate into a direct reduction in payload/spacecraft mass). However, one aspect that can be adjusted is the Jovian Moon Arrival date, which in the original specifications is listed as eighteen months (after Jupiter arrival). Figure 2 is once again shown at right (as Figure 5), with the Sun overlap removed, so that the cyclic nature of the Mars overlap can be clearly seen. One method of removing the competition for the same tracking support is to change the date of JMOI to one where there is no overlap between the Mars and the JME viewperiods.

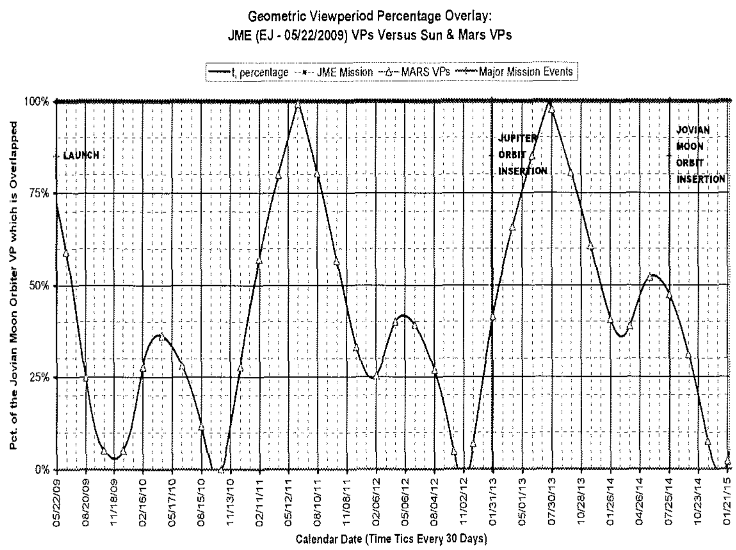


Figure 5: The repeating Pattern of the JME-Mars VP Overlap

In the case of the 2009 JME Launch date, the original Jovian Moon arrival occurs on 07/26/2014, at a time when the Mars contention is 44.1% during the Prime Mission. By "delaying" the date of the Jovian Moon arrival by 148 days (to 12/21/2014), this geometric overlap is reduced to 0.1% during the Prime Mission. Similar optimizations were performed for all launch opportunities, with the results presented in Table 4:

Table 4: Tracking Coverage Overlap Between JME and Mars Viewperiods

Contention for Optimized Jovian Moon Arrival Date

Launch Date	Launch-L+30d	EJ Cruise	JOI – 30d JOI + 5d	Orbit Reduction	Moon Approach	Prime Mission	Extended Mission	JMOI moved (days)	Optimized JMOI date
12/21/04	54.3%	26.3%	1.7%	47.0%	0.5%	0.0%	2.8%	65	11/14/09
01/11/06	10.8%	41.5%	2.9%	55.4%	0.5%	0.0%	2.8%	-24	11/14/09
02/13/07	45.4%	22.2%	91.4%	25.6%	1.8%	0.0%	9.0%	-63	07/24/10
04/01/08	0.2%	43.6%	92.9%	36.4%	3.3%	0.0%	16.2%	-49	10/17/12
05/22/09	64.8%	34.6%	32.7%	57.3%	2.9%	0.1%	17.0%	148	12/21/14
06/06/10	0.2%	48.6%	25.4%	53.3%	38.9%	36.4%	45.3%	16	02/20/14
07/11/11	61.6%	40.8%	61.5%	40.2%	2.9%	0.1%	17.0%	-167	12/21/14
08/14/12	2.6%	57.2%	28.9%	54.8%	49.2%	46.7%	54.6%	3	04/12/16
10/25/13	76.1%	54.0%	41.3%	34.6%	2.5%	0.0%	15.3%	-282	04/25/19
10/20/14	4.0%	60.2%	24.3%	53.5%	41.6%	39.6%	45.6%	24	06/26/18
11/20/15	67.7%	44.4%	92.8%	43.4%	2.5%	0.0%	15.3%	-105	04/25/19
12/23/16	1.6%	50.1%	80.3%	54.1%	2.4%	0.1%	11.0%	-14	07/22/21
01/16/18	71.1%	41.9%	80.5%	44.5%	2.4%	0.1%	11.0%	-121	07/22/21

Some of the viewperiod overlaps can be reduced from near total contention, to almost zero contention, as shown in Table 5 below. Note that while it is possible to minimize/optimize the overlaps, it is not possible to remove all overlaps. Some JMOI dates occur during the local minimum in the middle of the overlap cycle, and reduce to ~40% geometric overlap, but is still an improvement. Additionally, some of the JMOI dates are now placed such that the Jovian Orbit Reduction campaign must be actually solved to see if it is possible, rather than merely positing a solution as existing. Cases where the JMOI date is delayed, or moved by a modest amount should be possible, but the 10/25/2013 JME, where the Orbit Reduction has been reduced from 510 days to 228 days may not be possible to achieve.

Table 5: Tracking Coverage Overlap Improvement by Optimizing Jovian Moon Arrival Date

Negative Numbers indicate a reduction in viewperiod overlap

Launch Date	Launch-L+30d	EJ Cruise	JOI - 30d JOI + 5d	Orbit Reduction	Moon Approach	Prime Mission	Extended Mission	JMOI moved (days)	Optimized JMOI Date
12/21/04	0.0%	0.0%	0.0%	-3.8%	-24.9%	-10.6%	2.3%	65	11/14/09
01/11/06	0.0%	0.0%	0.0%	2.6%	0.5%	0.0%	-6.0%	-24	11/14/09
02/13/07	0.0%	0.0%	0.0%	3.1%	-2.5%	-15.8%	-27.3%	-63	07/24/10
04/01/08	0.0%	0.0%	0.0%	3.3%	0.5%	-18.5%	-26.1%	-49	10/17/12
05/22/09	0.0%	0.0%	0.0%	-6.7%	-46.9%	-44.0%	-13.6%	148	12/21/14
06/06/10	0.0%	0.0%	0.0%	-0.3%	-3.8%	-0.5%	3.7%	16	02/20/14
07/11/11	0.0%	0.0%	0.0%	7.0%	-55.7%	-69.2%	-65.7%	-167	12/21/14
08/14/12	0.0%	0.0%	0.0%	0.0%	-0.6%	0.1%	0.5%	3	04/12/16
10/25/13	0.0%	0.0%	0.0%	-0.1%	-75.3%	-87.2%	-78.1%	-282	04/25/19
10/20/14	0.0%	0.0%	0.0%	-0.2%	-6.3%	-1.0%	3.1%	24	06/26/18
11/20/15	0.0%	0.0%	0.0%	7.8%	-27.4%	-41.7%	-39.0%	-105	04/25/19
12/23/16	0.0%	0.0%	0.0%	1.4%	2.2%	-1.3%	-5.0%	-14	07/22/21
01/16/18	0.0%	0.0%	0.0%	9.1%	-24.8%	-36.7%	-41.1%	-121	07/22/21

Ranking the specific JME Candidate Trajectories

The ranking of the trajectory options presented in Table 6 is based upon the criteria discussed in this paper, and includes a weighting factor toward shorter mission durations, and higher payload capabilities; however, when those factors were not extreme, the ability of the DSN to support/provide tracking coverage was the determining factor in the ranking.

Table 6: Ranking of the Direct Earth-Jupiter Trajectory Options for the JME Mission

		Trajectory	Mission	JME/Mars Viewperiod Overlap				
Overall Ranking	Launch Date	Launch C3 (km^2/s^2)	Duration (years)	Orbit Reduction	Moon Approach	Prime Mission	Extended Mission	JMOI Date
	12/21/04	76.40	4.89	47.0%	0.5%	0.0%	2.8%	09/10/09
1)	01/11/06	75.90	4.07	55.4%	0.5%	0.0%	2.8%	12/08/09
2)	12/23/16	75.98	4.78	54.1%	2.4%	0.1%	11.0%	08/05/21
3)	02/13/07	79.11	3.78	25.6%	1.8%	0.0%	9.0%	09/25/10
4)	04/01/08	76.93	4.85	36.4%	3.3%	0.0%	16.2%	12/05/12
5)	01/16/18	76.28	4.01	44.5%	2.4%	0.1%	11.0%	11/20/21
6)	07/11/11	80.06	4.07	40.2%	2.9%	0.1%	17.0%	06/06/15
7)	06/06/10	83.39	3.83	53.3%	38.9%	36.4%	45.3%	02/04/14
8)	08/14/12	85.60	3.82	54.8%	49.2%	46.7%	54.6%	04/09/16
9)	11/20/15	88.42	3.88	43.4%	2.5%	0.0%	15.3%	08/08/19
10)	10/20/14	91.50	3.78	53.5%	41.6%	39.6%	45.6%	06/02/18
11)	05/22/09	82.77	5.35	57.3%	2.9%	0.1%	17.0%	07/26/14
12)	10/25/13	87.54	6.44	34.6%	2.5%	0.0%	15.3%	02/01/20

Summary

A simulated Jovian Moon Explorer mission was created to illustrate/explore the impact of providing Deep Space Network Tracking Support upon the mission design process for this mission.

Only the first level of optimization was conducted on the trajectories, so that the purpose of illustrating the use of different trajectories to consider/determine the availability of the DSN tracking coverage needed to actually support the mission could be clearly demonstrated.

Although this should make a reasonable starting point for the design of any impulsive missions from the Earth to Jupiter during the specified time frame, additional trajectory optimization and refinement should be conducted to a higher level of fidelity.

Such additional work should include the aspects which were either not considered within the scope for this paper, or was not fully optimized in the (preliminary) trajectories which were generated for presentation in this paper. These effects would include (but not be limited to) the use of Venus and Earth (and/or Mars) as swingby bodies for gravity assist maneuvers, deep space maneuvers, and other additional factors.

Any one of these additional considerations could refine the work presented in this paper significantly enough to cause a new "optimum" trajectory to be selected.

Conclusions

When planning the Jupiter Orbit Reduction Campaign (including swingbys of the Galilean Moons), the Jovian Moon Arrival Date should be selected to minimize DSN load/contentions. While it might not be possible to drive the contentions to 0%, by judicious selection of arrival date it is possible to minimize the contentions when the need for JME tracking support is greatest/most critical. The corresponding benefit to the mission is that they would receive DSN support/coverage to the fullest extent that is possible, and thereby increase their chance of being selected for additional project development (/funding).

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